14

Multiple Scattering at the Breakfast Table

white . . . is not a mere absence of colour; it is a shining and affirmative thing, as fierce as red, as definite as black.
G. K. Chesterton

The scene shown in Figure 14.1 is familiar enough. In it are the kinds of things likely to be found on your breakfast table: salt, sugar, and a glass of milk. Although dissimilar in many ways, they all are white. Why this is so is the subject of this chapter. And I can think of no better way to begin than with a simple demonstration.

Figure 14.1 Multiple scattering at the breakfast table.

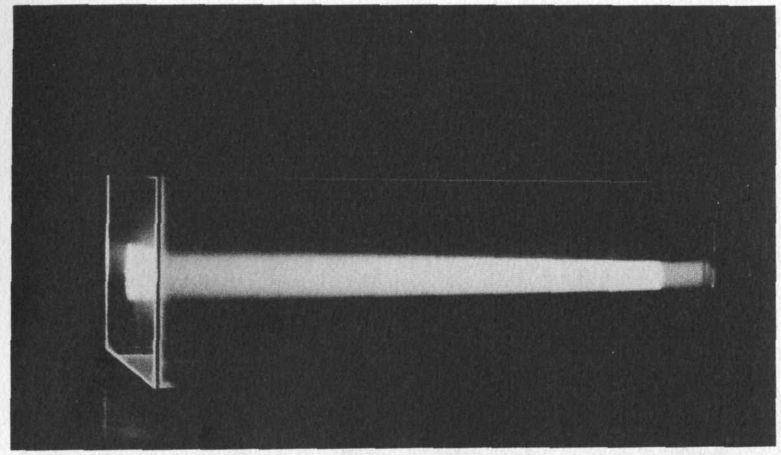

Figure 14.2 Single scattering by a suspension of fat globules (milk) in water.

SCATTERING IN AN AQUARIUM

Scattering of light by particles and by molecules was discussed in Chapters 11, 12, and 13. Without saying so, in these chapters I had in mind what is called *single* scattering in contradistinction to *multiple* scattering. The difference between the two kinds of scattering can be demonstrated using a slide projector, an aquarium filled with clean water, and some milk.

A slide projector in which an opaque slide with a hole in it is inserted provides a collimated beam of light. You cannot see this beam from the side unless it traverses a medium that scatters some of the light from the beam toward your eyes (this, by the way, is why movie scenes in which combating spaceships fire brilliant laser beams at one another are absurd: in space, where there is little to scatter light, you would see a beam only if it were pointed directly at you).

If the projector beam is shone into an aquarium filled with clean water you may, in a very dark room, barely be able to see the beam. To make it more evident add a few drops of milk to the water (Fig. 14.2). Milk contains tiny globules of fat which scatter light from the beam, and it is attenuated along the direction it propagates. Its margin is well defined as a consequence of single scattering: a photon (see the previous chapter) must be scattered at least once for us to see the beam (to be precise, we do not see the beam but rather the light removed from it), but its likelihood of being scattered more than once is small. To increase this likelihood add more milk to the water; that is, increase the concentration of scatterers. The result is shown in Figure 14.3. Note that light now comes from beyond the limits of the beam where previously none had been evident (Fig. 14.2). This is because photons scattered by particles in the beam are scattered again by particles outside it and thence to our eyes. Multiple scattering increases the number of ways in which a photon may reach our eyes.

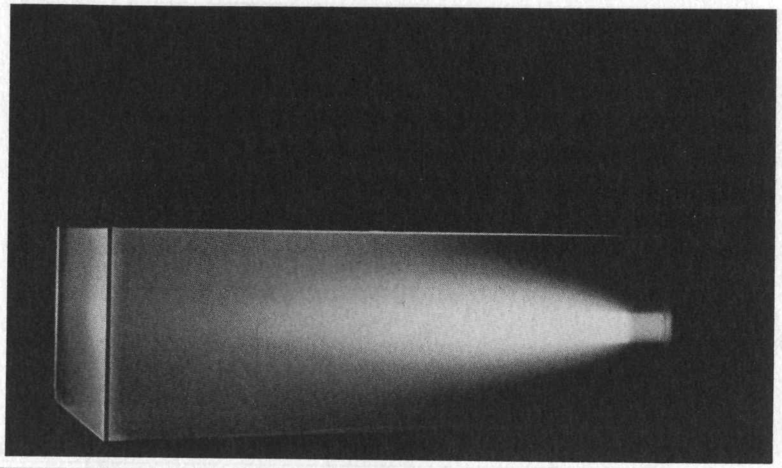

Figure 14.3 Multiple scattering by a suspension of fat globules (milk) in water.

A PILE OF PLATES

Plates cut from clear plastic sheets provide raw material for demonstrating other aspects of multiple scattering. One such plate, on a black background, is weakly reflecting; but a pile of them is strongly reflecting (Fig. 14.4). Here is an example of an ensemble—a pile of transparent plates—with optical properties quite different from those of its individual members. As plates are successively added to the pile it reflects more light, but beyond a certain number, in which instance the pile is said to be *optically thick,* each additional plate yields an ever smaller increment. So it is also with any optically thick scattering medium, such as a cloud. A single water droplet does not scatter much light, but because of multiple scattering an optically thick cloud of such droplets reflects much of the visible light incident on it, which is obvious to anyone flying over a thick layer of clouds.

For a collection of scatterers (e.g., a pile of plates, a cloud) to be bright and white upon illumination by white light it must not only be optically thick but its members must only *weakly* absorb such light. Consider a pile of plates in photon language. Most of the photons incident on a single plate are transmitted to the underlying black surface where they are absorbed. But with two plates in a pile some of the photons transmitted by the first are reflected by the second. Each plate added to the pile increases the probability that a photon eventually gets to your eyes, so with enough plates the pile is white. Again, as with the aquarium demonstration, multiple reflection (scattering) increases the number of ways—reflected once, twice, and so on—in which a photon can get to your eyes. But multiple scattering takes as well as gives: the greater the number of scatterers the greater the chance that a photon will be absorbed; multiple

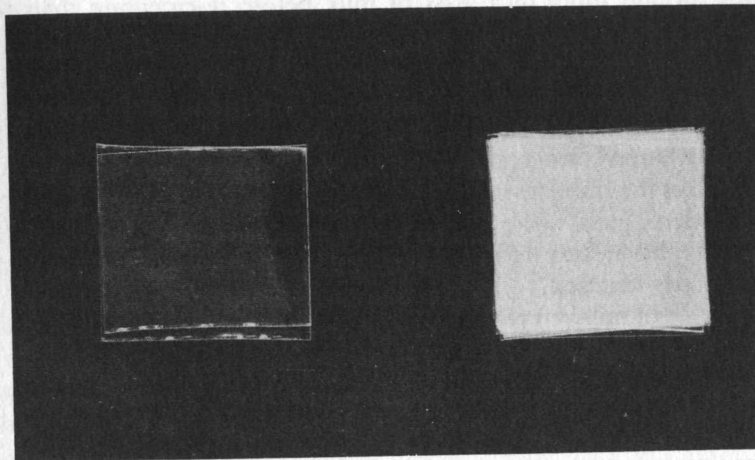

Figure 14.4 A pile of transparent plates on a black background.

scattering not only increases the pathways by which incident photons can reemerge from a medium, it exposes them to a greater hazard of being absorbed. I shall return to this later.

WHITE CLOUDS: THE CONVENTIONAL WISDOM

It has been stated countless times that clouds are white because they are composed of droplets sufficiently large that they scatter visible light of all wavelengths about equally. Indeed, this notion is so widespread and has so many adherents that it now transcends science and has become an article of faith; to believe it is a mark of piety. I can therefore anticipate the great howling that will be raised in response to my assertion that this explanation is demonstrably false. At the very least, those who advance it fail to distinguish between a *necessary* condition and one that is merely *sufficient*.

For a cloud to be white (upon illumination by white light) it is sufficient that its droplets scatter visible light of all wavelengths about equally—but it is not necessary. If it were, a glass of milk would be blue. For milk is a suspension of particles that, unlike cloud droplets, scatter blue light more than red light; this was why milk was used for the green flash demonstration discussed in the previous chapter. Yet a glass of ordinary milk is white, not blue. Why? The single-scattering characteristics of particles in milk are really quite irrelevant to the appearance of a glass of milk. What is relevant is that it is optically thick—a small glass of milk looks no different from a large glass—and its particles are very weakly absorbing. Although incident photons corresponding to the color red may have to rattle around more in a glass of milk before re-emerging than those corresponding to blue, almost all of them ultimately re-emerge having escaped absorption. It is these two characteristics—optically thick and weakly absorbing—that unite the dissimilar objects with which I began this chapter. Regardless of their single-scattering characteristics, if enough weakly absorbing particles are heaped into a pile it will be white if the source of illumination is white. Besides the examples of milk, salt, and sugar in Figure 14.1 there is snow, flour, powdered glass, white sand—the list is endless. Taken individually these particles may have vastly different scattering properties; collectively, however, they are nearly identical.

Every glass of milk refutes the conventional explanation of why clouds are white. In fairness to those who espouse it, I might add that the scattering characteristics of individual particles in optically *thin* clouds are relevant to their appearance. For example, thin cirrus clouds are white—although not nearly as bright as cumulus clouds—because their particles are large compared with visible wavelengths; in contrast, noctilucent clouds—very tenuous high-altitude clouds—are often described as bluish, which is offered as evidence of the smallness of their particles. But I think it also fair to say that people who ask why clouds are white do not have in mind wispy cirrus clouds but, rather, proper clouds: big, fluffy, towering cumuli.

As a harsh critic of what I consider to be superficial explanations, I would be wise to forestall criticisms of mine. It might be—indeed, has been—asserted that reflection and scattering are fundamentally different processes, in which instance the two experiments described in preceding paragraphs are unrelated: the first demonstrates multiple scattering whereas the second demonstrates multiple reflection. Such logic-chopping would make a medieval theologian blush. I argued in the previous chapter that the term scattering embraces reflection as well as refraction. We continue to use these terms separately for historical reasons (i.e., intellectual inertia) and because they are convenient ways of summarizing what is observed. But other than metaphorically, light does not bounce off of a window pane. What we call the light reflected by glass is the sum of all the light scattered by its constituent molecules; if we ignore these details it is for convenience not by necessity.

CLOUDS AND SNOW

You may have noticed that clouds are often not as bright as snow (Fig. 14.5). This is a variation on the black cloud theme, which was discussed in Chapter 11. Of course, to compare fairly a cloud with a snowpack the conditions of illumination and viewing must be identical, and this is not always easy to obtain. Nevertheless, I have yet to see clouds brighter than the brightest snow. This is not because cloud droplets are more absorbing than ice grains in snow. Indeed, the reverse is true: the ratio of incident light scattered to that absorbed

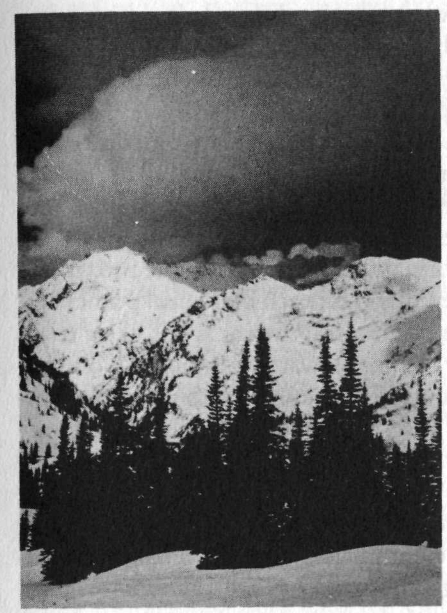

Figure 14.5 All else being equal, snowpacks are usually brighter than clouds, as in this winter scene near Alta, Utah.

by a single cloud droplet is *greater* than that by single ice grains in snow because the grains are much larger (see the next chapter for more on this).

Both clouds and snowpacks are multiple-scattering media. The difference between them lies in their different *optical* thicknesses, that is, their thicknesses measured in units of mean free paths (see Chapter 16). Snowpacks are usually optically thicker than clouds. Indeed, snow on the ground is often effectively infinitely optically thick. Except for very shallow snowpacks, the addition of another layer does not sensibly change the fraction of the incident light it reflects. You may have observed this many times. Snow a few inches deep is indistinguishable from that a few feet deep. Clouds are darker than snow not because they absorb more light—they absorb less—but because they transmit more of it to their surroundings.

AN APPARENT PARADOX

Before discussing yet another aspect of multiple scattering, there is one other matter to be disposed of. It may have occurred to you that every cloud presents what at first sight is a paradox. Water molecules, like all the other molecular constituents of the atmosphere, scatter light. But when a given amount of water vapor condenses to form droplets the resulting cloud scatters much more than the water molecules did. This was evident in the cloud bottle demonstration of Chapter 2. It is not the amount of water in a cloud that makes it appear so different from the patch of sky in which it was born but rather the state of aggregation of this water. Why? The answer lies in the concept of coherence, which I discussed briefly in the previous chapter.

A group of water molecules when randomly separated scatter incoherently; when these same molecules condense into a droplet (i.e., they all are part of the same entity rather than independent agents) they scatter coherently. And coherent scattering can be much more intense, all else being equal, than incoherent scattering. Suppose that a group of hare-brained people is trying to push a stranded car. If they push incoherently (i.e., each individual pushes randomly when and in whatever direction he chooses) the car is not likely to do more than rock back and forth, possibly inching forward laboriously. Now suppose that a leader emerges from the group and urges everyone to push coherently: One, two, three, Push! In no time at all the car will be on its way. I have implicitly assumed that the pushing is done coherently *in phase:* coherence by itself is not sufficient unless directed to the same end (I shall have more to say about coherent scattering in Chapter 18). Just as coherent (in phase) pushing yields a much greater effect than incoherent pushing, so also is coherent scattering vastly more intense even though the scatterers are the same in both instances.

While I am on the subject of coherence and incoherence I should note that although a single cloud droplet is a coherent scatterer, a group of them scatters incoherently. If you are reeling after this apparent contradiction, I'll back up a bit. A group of N isolated water molecules in the atmosphere scatters incoherently: scattering by N is N times scattering by one. But when these same N molecules condense to form a droplet, scattering by them is much greater. Now consider a group of water droplets. If they are as far apart as those in atmospheric clouds, scattering by N droplets is N times scattering by one. That is, the droplets considered as a group are incoherent scatterers, whereas each droplet itself is a group of coherent scatterers. The multiple scattering I have discussed in this chapter (and will discuss further in subsequent chapters) is incoherent multiple scattering. Now let us imagine that a cloud of water droplets is compressed until it forms a continuous film. Again, what is observed is predominantly coherent scattering, more intense than incoherent scattering by the cloud but confined mostly to two directions. For example, sunlight reflected by a film of water is much brighter than that reflected by a cloud, at least a thousand times greater, possibly much more depending on the angle of incidence of the sunlight (to convince yourself of this compare the reflection of the sun in a pond with light from a cloud). But this reflected light is concentrated in a single direction, that given by the law of reflection, whereas the cloud scatters light in all directions. Light from the fogged mirror of Chapter 7 has about the same brightness in all directions; the unfogged mirror is much brighter, but only in one direction.

In going from a group of independent molecules to independent droplets

to a water film, nothing changes except the arrangement of the molecules. Chemically they are the same. Yet what is observed is markedly different depending on the degree of coherence—the extent to which the molecules stick together, both figuratively and literally—of their scattering.

ANOTHER PILE OF PLATES

As long as we have plastic plates at hand we might as well use them to demonstrate yet another salient characteristic of multiple scattering: a little bit of absorption goes a long way. In the following section the relevance of this demonstration to the atmosphere is discussed.

I implied that the plates shown in Figure 14.4 are weakly absorbing. And so they are. But they are not nonabsorbing. To show this, take a single plate and lay it on a white background. Then add plates. With each additional plate the pile gets darker (Fig. 14.6). Multiple reflection exposes photons to multiple opportunities to be absorbed by the plates. The piles of plates in Figures 14.4 and 14.6 do not look the same because of different contrast and because they were photographed under different illumination and at different exposure times. Yet the two piles have the same reflectance (fraction of incident light reflected), which is independent of the underlying surface if the pile is optically thick. You can verify this with a pile of plates that straddles the boundary between black and white pieces of paper.

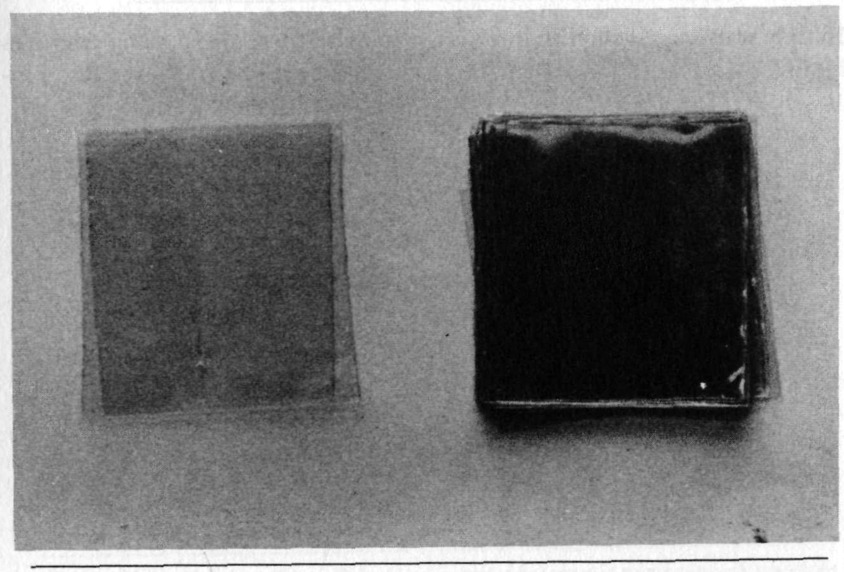

Figure 14.6 The same pile of plates as in Figure 14.4 but on a white background.

CLOUDS AT INFRARED WAVELENGTHS

The clouds we perceive to be so bright are much darker at infrared wavelengths. This is because absorption by water—liquid or solid—increases at wavelengths longer (and shorter) than those of visible light. And because of multiple scattering, absorption does not have to be great before a cloud of water droplets becomes quite dark; most respectable clouds will be black to radiation with wavelengths greater than 3 μm (the wavelengths of visible light lie between about 0.4 and 0.7 μm). We cannot see such dark clouds, of course. What we do see often misleads us.

One sometimes encounters—on examination papers if nowhere else—the assertion that it is warmer on cloudy nights because the clouds "reflect" infrared radiation back to earth. They do no such thing, no more than the tree and the sand in Chapter 10 reflect it. Water is so much more absorbing of infrared radiation emitted by terrestrial objects than of visible radiation that all but the thinnest clouds absorb nearly all the terrestrial radiation incident on them. Clouds also emit infrared radiation, which is where the confusion lies. Such radiation is not derived, except indirectly, from the incident terrestrial radiation; in contrast, the light we see from clouds has been derived from incident sunlight: we do not see them at night. Clouds, however, emit day and night; they keep the earth warm at night because they emit more infrared radiation than the clear sky.

MULTIPLE SCATTERING AT THE BEACH

Multiple scattering is such an intersting topic and there are so many examples of it in nature that I shall devote the next chapter to exploring it further. I invite you to leave the breakfast table and go to the beach.